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Experimental Comparison of Gains in Achievable Information Rates from Probabilistic Shaping and Digital Backpropagation for DP-256QAM/1024QAM WDM Systems

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Abstract *Gains in achievable information rates from probabilistic shaping and digital backpropagation are compared for WDM transmission of 5×10 GBd DP-256QAM/1024QAM up to 1700 km of reach. The combination of both techniques is shown to provide gains of up to ~ 0.5 bits/QAM symbol.*

Introduction

In order to improve the performance with respect to the achievable information rates (AIRs) of coherent system employing quadrature amplitude modulation (QAM) formats, effort has been directed to optimization of transmitters and receivers. For large QAM constellations, two approaches that lead to AIR improvements are constellation shaping^{1–3} and fiber nonlinear impairments compensation⁴. At high signal-to-noise ratio (SNR) values, the AIR of large order QAM formats with uniform input distribution present shaping loss. In order to reduce it, constellation shaping techniques can be applied. In the optical fiber channel, the interaction between chromatic dispersion and Kerr nonlinear effects ultimately limits the AIRs at high SNR. Nevertheless, there has been an increasing interest on applications of shaping techniques to the optical channel^{1,2,5,6}. The AIRs on the optical channel can also be increased by performing digital backpropagation (DBP) using the split-step Fourier method (SSFM) to compensate the deterministic Kerr nonlinear impairments in each WDM channel⁷. Since both approaches require additional complexity in the transceiver implementation, an important question yet to be clarified is how much benefit can be provided by each one, enabling a better perspective on the performance gain versus implementation complexity trade-off.

In this paper, the first experimental investigation of AIR performance gains provided by probabilistic shaping, DBP, and the combination of both for a WDM system is performed. The system under investigation is composed by five carriers modulated at 10 GBd with dual-polarization (DP)-256QAM and DP-1024QAM.

Experimental setup

The experimental setup is depicted in Fig. 1. At the transmitter, offline DSP is used to gen-

erate the sequences of coded data symbols for four distinct constellations: uniform 256QAM, shaped 256QAM, uniform 1024QAM, and shaped 1024QAM. The probabilistic shaping method applied is based on the dyadic approximations of the optimum symbol input distributions for a large QAM constellation^{2,3}. Quadrature phase-shift keying (QPSK) pilot symbols for equalization and carrier phase recovery are inserted within the stream of data symbols at a 2% rate. The sequence of complex symbols is upsampled and pulse shaped by root-raised cosine filter with rolloff factor of 0.5. The data is digital-to-analog converted by a 64 GSa/s arbitrary waveform generator (AWG) with 20 GHz of bandwidth and amplified by RF linear drivers. The baseband signal drives the optical in-phase and quadrature (IQ) modulators. Two modulators are used to modulate the WDM carriers. The first one modulates a sub-kHz linewidth fiber laser (Koheras BasiK C-15), which is used to modulate the channel of interest (COI). The second modulates the remaining four WDM carriers (external cavity lasers, ECLs, ≤ 100 kHz), which are subsequently split with a wavelength selective switch (WSS), decorrelated in time, and recombined with the channel of interest. To measure the system WDM performance, the fiber laser position in the 25 GHz frequency grid is systematically swapped with its corresponding ECL neighbors, such that all WDM channels are measured with the same sub-kHz linewidth laser. The WDM channels are sent to the delay-and-add polarization multiplexing emulator stage which provides the dual-polarization signal.

The WDM transmission is done using a recirculating loop composed by two 50 km spans of standard single mode fiber (SSMF), an optical bandpass filter, a 2-by-2 coupler (3 dB) and two acousto-optic switches. All fiber losses are

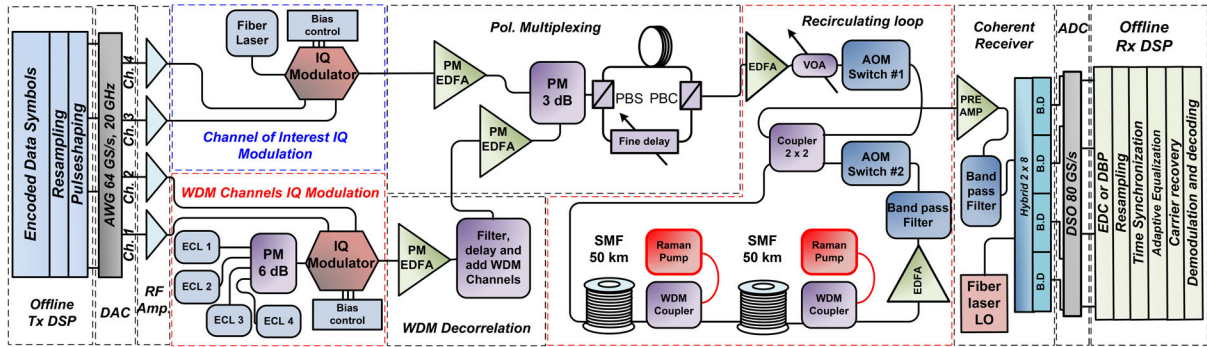


Fig. 1: Experimental setup for WDM generation, transmission, coherent detection, and offline DSP processing of 5×10 GBd DP-256QAM/DP-1024QAM.

compensated by Raman amplification (backward pumping per span, 26 dBm@1450 nm). The remaining losses are compensated by an Erbium-doped fiber amplifier (EDFA). At the loop output, the signal is pre-amplified, filtered, and detected with an optical coherent receiver. The local oscillator used by the coherent receiver is also a fiber laser with sub-kHz linewidth (Koheras BasiK E-15). The detected signal is acquired with a real time sampling oscilloscope at 80 GSa/s and 33 GHz of bandwidth. The data is processed offline. The flow of DSP algorithms is composed by low pass filtering, single channel DBP or electronic chromatic dispersion compensation (EDC), resampling, timing recovery, pilot assisted adaptive equalization with the constant modulus algorithm (CMA), carrier phase recovery⁸, demodulation and decoding. The DBP algorithm is performed using a non-iterative symmetric SSFM⁷ to solve the Manakov approximation of the coupled mode nonlinear Schrödinger equation (NLSE) with a fixed step size.

Estimation of AIR

For all results presented in this paper, the AIR is estimated after synchronization, equalization, and carrier recovery. An auxiliary probability distribution describing the input-output behavior of the channel is assumed, since the input-output (X, Y) relation of the fiber-optic channel is not available in closed form. The Tikhonov distribution based phase recovery algorithm⁸ used directly produces the posterior probability distributions $p(X|\hat{Y})$, where X is a random variable describing the QAM symbols at the input of the channel and \hat{Y} is the output of the equalizer. The AIR is then numerically estimated over long sequences of received data ($\geq 10^5$ QAM symbols per polarization) by calculating the mutual information $I(X; \hat{Y}) = H(X) - H(X|\hat{Y})$, where $H(X)$ is the entropy of the input distribution and $H(X|\hat{Y})$ is the entropy of the posterior probability distribution. The estimated AIRs are independent of the

channel code, and are only a function of the receiver processing, including the EDC/DBP, synchronization, equalization and carrier phase recovery performed, and the input distribution.

Results and discussions

The results shown in this section corresponds to the performance of the system at the optimum *total* launched power, which was observed to be around -5 dBm for all tested configurations before DBP. Single channel DBP was applied using the largest step size for the SSFM that allowed the maximum AIR gain from the algorithm, found to be 12.5 km (4 steps/span).

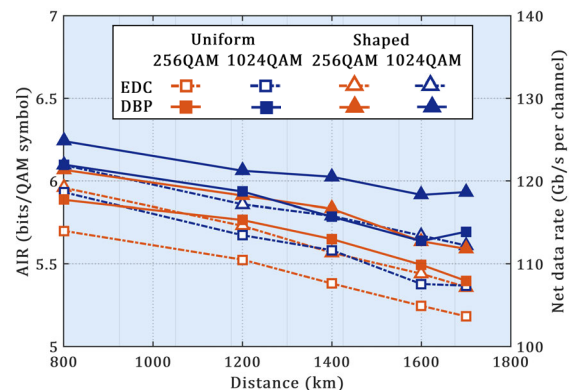


Fig. 2: Estimated AIR of the central WDM channel versus distance for all investigated cases.

Figure 2 shows the estimated AIR of the central WDM channel as a function of the transmission distance for all investigated configurations. The lowest AIR is exhibited by uniform DP-256QAM without DBP, which achieves 5.2 bit/s/QAM symbol (104 Gb/s) at 1700 km of reach. For the same reach, the best performance is obtained for shaped DP-1024QAM with DBP - 5.9 bits/QAM symbol (118 Gb/s). The remaining cases, situated in between these two extremes, can be used to isolate the AIR gains provided by probabilistic shaping and DBP. From the curves one can observe that uniform DP-256QAM with DBP, shaped DP-256QAM, and uniform DP-1024QAM present approximately the

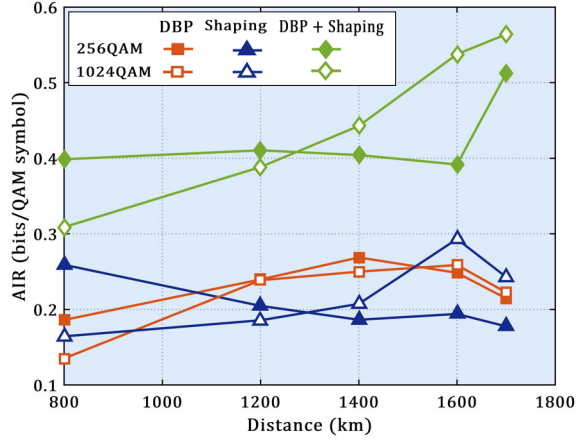


Fig. 3: Gain in AIR of the central WDM channel w.r.t. the uniform distributed constellation performance applying only EDC.

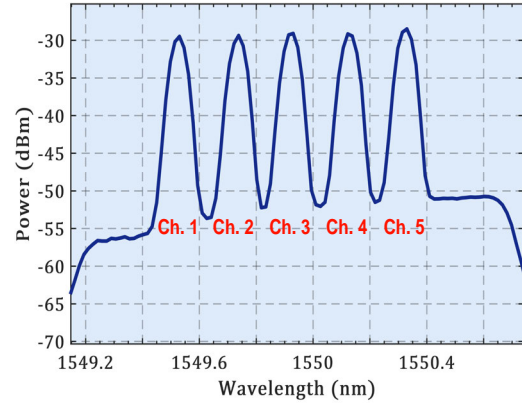
same AIR for all studied distances. The same conclusion can be drawn for the configurations uniform DP-1024QAM with DBP, shaped DP-1024QAM, and shaped DP-256QAM with DBP.

Figure 3 shows the AIR gains provided by probabilistic shaping, DBP and the combination of both w.r.t. the transmission of the respective uniform distributed constellation, as a function of the reach. The similarity between AIR gains from shaping and DBP can be verified. The variations of the shaping gain can be attributed to the imperfect processing and statistical variations due to the limited size of data sequences. Moreover, the gain resulting from the joint application of both techniques is virtually equal to the sum of the gains obtained by applying each technique separately. The maximum gain is verified to be between 0.5 to 0.6 bits/QAM symbol for shaped DP-1024QAM with DBP.

Figure 4 shows the spectrum and the estimated AIR for each of the five WDM channels after 1700 km of transmission distance of shaped DP-1024QAM, with and without DBP. Although there is a tilt in the noise spectrum, all inner channels reach quite similar performance. A small deviation can be noticed in AIR performance (see the table in Fig. 4) of the outer channels due to the fact those are the ones who mostly differ in the optical SNR (OSNR). Nevertheless, the results demonstrate very similar performance gains for the central channel and its WDM neighbors.

Conclusions

The experimental results presented show that systems using DP-256QAM and DP-1024QAM modulation formats may have similar benefits in achievable information rates from probabilistic constellation shaping and digital backpropagation. The use of both techniques allowed a maximum improvement of 0.5 to 0.6 bits/QAM symbol, observed after 1700 km transmission of DP-



AIR in bits/QAM symbol

Channel #	1	2	3	4	5
Shaped 1024QAM	5.55	5.53	5.37	5.65	5.6
Shaped 1024QAM + DBP	6.06	5.93	5.93	5.99	5.79

Fig. 4: Received spectrum and estimated AIR for all WDM channels for shaped 1024QAM with and without digital backpropagation after 1700 km of transmission.

1024QAM.

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